Design and Analysis of Low Earth Orbit Satellite Communication System Based on MBSE

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Abstract. Low Earth Orbit satellite communication has become an important part of the integrated network between earth and space, offering low-latency, seamless communication services that are available everywhere. Adopting a Model-Based Systems Engineering approach to digital design has grown in importance as a way to deal with the complexity of such a system and increase the effectiveness of system design. The paper presents the initial design of the LEO satellite communication system architecture and demonstrates how MBSE, using the System Modeling Language (SysML), can better comprehend and analyze the system's functionality and architecture, meet stakeholder requirements, and extend the model results to the full lifecycle of system development. MBSE-based development improves the model's consistency and reusability. Based on the analysis of the requirements of the LEO access network, bearer network, and core network, the design methods and ideas of models, including the core element model refinement, communication scenario use case and activity design, satellite communication payload logical architecture design, and SysML model integration simulation analysis. The results of these models can provide support for the architecture design and key technology verification of the LEO satellite communication system.

Keywords: LEO · Satellite · MBSE · SysML · Model

1 Introduction

In recent years, Low Earth Orbit (LEO) satellite communication system has witnessed rapid development due to the continuous advancement and commercialization of satellite communication technology. This system offers several advantages, including global coverage, high-speed transmission, and low latency, making it an excellent extension of ground networks [1]. The introduction of the 5G NTN standard led by 3GPP and the ongoing evolution of the 6G standard have further solidified LEO satellite communication technology's position as a crucial component of integrated space-ground networks, attracting significant attention. The construction of a LEO satellite communication system is a complex system engineering endeavor that imposes higher requirements

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compared to traditional satellite communication system construction. These requirements encompass application scenario demands, the number of networked satellites, core technology challenges, and iterative evolution capabilities. However, the traditional document-based interaction patterns for LEO constellation communication system design exhibit several shortcomings, including information ambiguity and difficulties in document maintenance. These limitations hinder the ability to achieve seamless interaction throughout the system's life cycle design.

SysML based on the Model-Based Systems Engineering (MBSE) method is a system modeling language widely used in complex system architecture and software and hardware system design, especially suitable for the full lifecycle design and interaction of complex systems [2]. Based on the SysML, the satellite communication system can be analyzed by establishing models of different levels to describe the system's components, functions, interaction relationships, etc., to better understand and design the system. A detailed introduction to the development of the MBSE field and the SysML modeling technology based on MBSE has been widely applied in various complex system designs [3, 4]. A standard model-based system architecture for CubeSat missions is presented [5]. MBSE and SysML to model a standard CubeSat and apply that model to an actual CubeSat mission, the Radio Aurora Explorer mission, developed by the Michigan Exploration Lab and SRI international [6]. Based on the results of the previous works, the researchers of the same team carried out further research work, Model-based approach was utilized for RAX CubeSat mission system modeling using SysML, which helps integrate other discipline-specific engineering models and simulations.[7] MBSE method for satellite communication system architecture design, which improves complex system design capabilities [8]. A thesis devoted to enhancing Cameo Systems Modeler, a traditional commercially available MBSE software, through its integration with multidomain simulations of the system's dynamics developed in Matlab/Simulink development environment, which can improve co-simulation capabilities [9]. A comprehensive description of the system architecture and key technology development is provided in the field of LEO constellation network construction [10].

This paper is organized as follows. Section II, provides an overview of the development status of the LEO satellite, including the parameters of satellite constellations such as Starlink and OneWeb, and then reviews the general system architecture and core network elements. Section III, the development and modeling methods of the SysML modeling language based on MBSE technology are described. In Section IV, the requirements analysis is carried out first around the access network, bearer network, and core network of the LEO satellite communication system. Secondly, use cases are extracted from the core scenarios of communication and modeled. Furthermore, the communication payload software logic architecture and the state machine of the elements are modeled. Finally, taking Doppler simulation in LEO as an example, a joint simulation design method based on SysML is presented. The paper concludes with future research directions listed in Section V.

2 Development and Architecture Analysis of the LEO Satellite Communication System

Several companies around the world have invested in the research and operation of LEO satellites. LEO constellations can be used not only in traditional fields such as mobile communication and internet access but also in areas such as remote sensing monitoring, military communication, and ocean monitoring.

Major satellite constellations include SpaceX's Starlink, OneWeb, Amazon's Project Kuiper, and Telesat. Among them, Starlink is currently developing the fastest, to provide services in the northern US and Canada by 2020, and expand its service range to nearly global by 2021 (see in Table 1). As of February 2023, the number of Starlink satellites in orbit has exceeded 3,500. SpaceX has also proposed its second-generation Starlink plan, which will rely on Starship launch and form a satellite constellation with up to 29,988 satellites [11].

Table 1. Constellation parameters

Constellation	Satellites	Plane	Orbit altitude	Inclination
Starlink	3500 +	72	550 km	53°
OneWeb	648	18	1200 km	87.9°
Telesat	298	8	1014 km	98°
Project Kuiper	3236	98	630 km	51.6°

The deployment of LEO constellations can be achieved by using both polar-orbiting satellites and inclined-orbiting satellites, which can achieve global coverage. Scenario simulation (illustrated in Fig. 1), conducted using Satellite Tool Kit (STK) software, can effectively guide the design of LEO constellations.

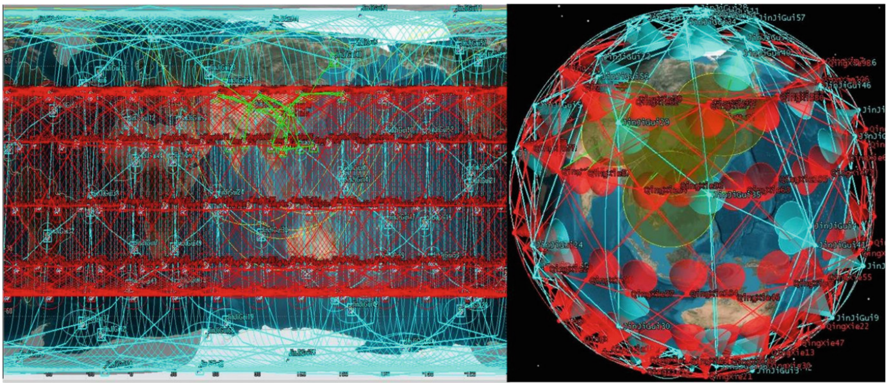

Fig. 1. 2D/3D Scene Simulation of LEO Satellite

The LEO satellite communication system architecture mainly consists of three segments [12]: user segment, space segment, and ground segment (shown in Fig. 2).

- User Equipment (UE): mainly includes handheld, vehicle-mounted, airborne, ship-borne, and fixed terminals, to realize the access function with user services.
- User Link: the link between the terminal and the satellite or base station, realizing broadband and narrowband communication services for users. Broadband mainly uses the Ku/Ka frequency bands, and narrowband users mainly use the L frequency band.
- Space Segment: mainly composed of polar orbit satellites and inclined orbit satellites, with onboard data processing and data transmission capabilities, and further carrying out functions such as navigation enhancement and earth observation.
- Inter-Satellite Links (ISL): using the inter-satellite microwave or laser links to achieve routing and switching functions.
- Feeder link: the data transmission link between the satellite and the ground control station, mainly carrying high-speed data in the Q/V frequency bands to realize the satellite's ground access capability.
- Gateway: responsible for communication between the ground network and the satellite network, completing the satellite network protocol conversion function.
- Network Operations Center (NOC): responsible for configuring space network resources and managing the LEO satellite network.
- Telemetry, Tracking, and Command (TT&C) System: responsible for remote control and telemetry of LEO satellite constellations.
- Core Network (CN): the public core network used by the LEO satellite communication system and ground network, realizing core functions such as user registration, authentication, access, and exit.

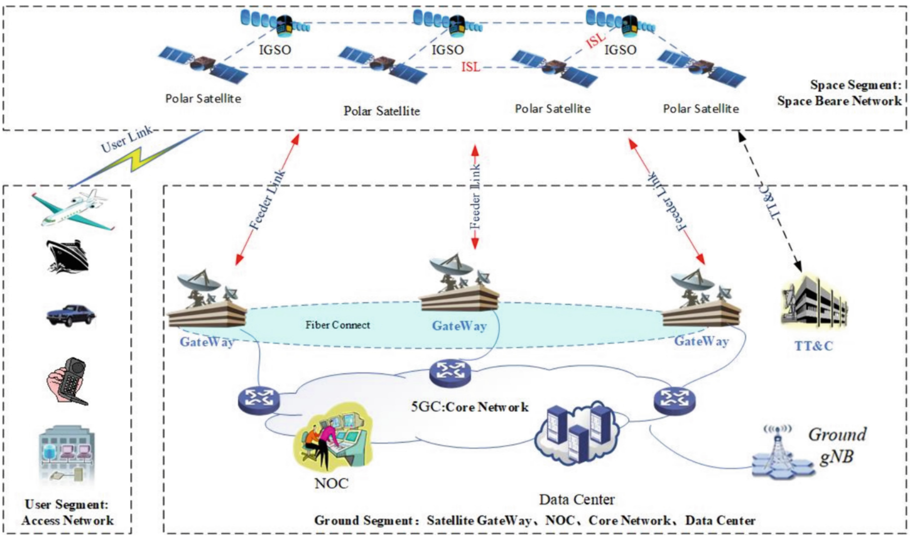

Fig. 2. LEO satellite communication system architecture

3 Overview of MBSE-Based Methodology

MBSE is an approach to system design that utilizes models as the central means of capturing and communicating system requirements, architecture, and behavior. SysML is a graphical modeling language that is used to create models of systems and their components [13, 14]. It is a profile of the Unified Modeling Language (UML) that has been tailored to meet the needs of systems engineering [15].

The combination of MBSE and SysML provides powerful schemes for designing and analyzing complex systems. By using SysML to create system models, engineers can effectively capture and communicate system requirements, architecture, and behavior, leading to improved collaboration and reduced errors in the design process.

MBSE and SysML also allow for the creation of simulations and other analytical tools that can be used to validate system designs and identify potential issues before implementation. This helps to reduce costs and improve system reliability.

Overall, MBSE and SysML offer a systematic, model-driven approach to systems engineering that can greatly improve the design and analysis of LEO satellite constellations and other complex systems.

The digital modeling and design of the LEO satellite communication system are mainly accomplished through the MBSE-based SysML design method, which covers the requirements diagram, behavior diagram, and structure diagram (shown in Fig. 3).

The method establishes a fully digital model of system control flow and information flow, covering the key network elements of the system and defining the operational processes of critical functions. The following describes the meanings of diagrams in SysML (see in Table 2).

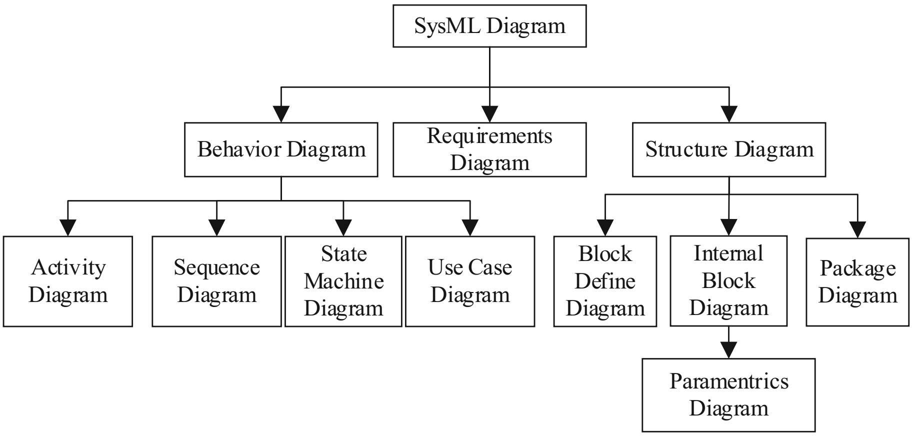

Fig. 3. Classification of SysML diagrams

Table 2. SysML diagrams

Diagram	Function Description
Package diagram	The Package Diagram illustrates the hierarchical relationships between different model elements and manages the modules in the file using packages, making the management of the system model clearer and more convenient
Activity diagram	The Activity Diagram illustrates the inputs, outputs, and control flow of an activity, as well as how the activity transforms inputs into outputs. It is used to illustrate the complete process of system operation
Sequence diagram	The Sequence Diagram is a dynamic view that illustrates the interactions between system elements, including the calling of operations and the exchange of messages
State machine diagram	The State Machine Diagram emphasizes the states of a block and the transitions between states triggered by time or events
Use case diagram	The Use Case Diagram describes how actors use the system to achieve a specific goal. Use cases are typically defined as a series of actions performed by the system that produce valuable observations for the actors
Requirement diagram	The Requirement Diagram describes the requirements of the system graphically, showing the relationships between requirements such as inclusion and inheritance. These requirements typically represent the functions and performance that the system is expected to achieve
Block definition diagram	The Block Definition Diagram represents the structural elements and their relationships in terms of blocks. Elements included in the Block Definition Diagram are blocks, actors, value types, constraint blocks, flow ports, and interfaces, which form the basis of other elements in the system
Parametric diagram	The Parametric Diagram represents the attributes and constraint relationships of a block and further illustrates the internal structure of the block. These constraints are typically represented as equations or inequalities
Internal block diagram	The Internal Block Diagram reflects the internal structure of a block, including its attributes and the connections between internal blocks

4 MBSE-Based Methods for Low Earth Orbit Satellite Communication System Architecture Design

4.1 Functional Requirements Decomposition

Regarding requirement analysis, the work is carried out mainly in three dimensions: access network, space-bearing network, and core network. To meet the above functional requirements, the core network components in the LEO system architecture are identified through requirement analysis, including User Equipment, Gateway, Satellite-gNB, Protocol-Gateway, Space-based Network Controller, Satellite Router, Access Gateway, Core Network, Network Operation Center, TT&C System. The main function requirements are as follows:

- The access network serves users by providing access to satellite and ground-based services, meeting the access requirements of large user volumes and different station types. Through a coordinated management and control mechanism between space and ground, it realizes wireless resource scheduling of beam, frequency, time slot, power, and other parameters, meeting the application requirements of multi-user, multi-rate, and interconnectivity between any nodes.
- The space-based bearer network serves as the carrier for inter-satellite and satellite-ground information transmission. The space-based carrier network is composed of ISL and Feeder Link, adopts routing switching technology based on label identification switching, completes information forwarding for network access and network entry, and provides high-speed transmission for Internet services.
- The core network is designed based on the Core Network system and adopts a service-oriented network architecture. It supports the separation of control and forwarding functions and provides services such as service activation, authentication, authorization, user management, and data forwarding for the broadband network.

Based on the above analysis, the core network elements are modeled using Block Definition Diagram (BDD), (shown in Fig.4).

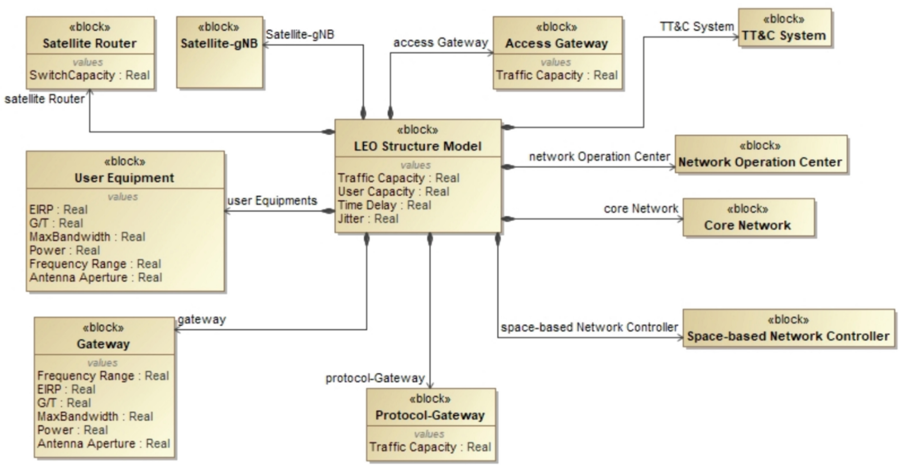

Fig. 4. LEO satellite communication system structure model

4.2 Communication Scenario Use Cases and Activity Analysis

Based on the analysis of the core communication process use case scenarios, the system's operation process under each scenario is demonstrated through modeling, identifying, and analyzing the external interaction relationships, fully capturing the requirements of stakeholders, and improving the system-level internal and external interface requirements. The operation scenarios and various usage conditions of the LEO satellite communication system throughout the entire life cycle are analyzed, and the system's relevant functional use cases were obtained. A use case diagram is used to analyze the interaction relationships between the system and the various elements in the usage environment. Based on this analysis, the core use case model for the LEO communication field is summarized. It consists of the network initial activation process, user equipment access, and registration process, user equipment-to-ground network communication process, ground-to-user equipment business communication process, end-to-end business communication process, and user equipment handover process across satellites (shown in Fig. 5).

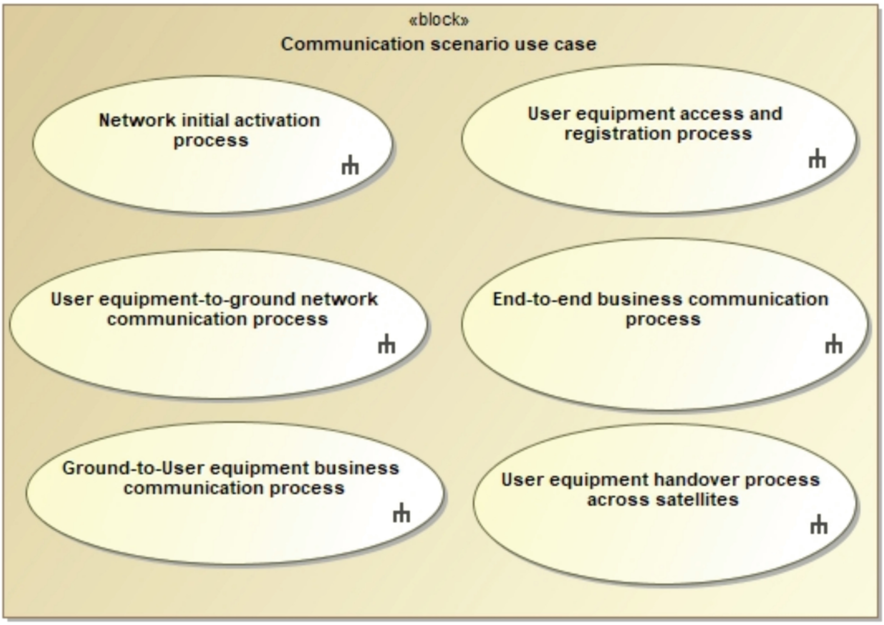

Fig. 5. Communication scenarios use case model

For example, the user equipment-to-ground network communication process mainly involves elements such as satellite-gNB, user equipment, gateway, access gateway, core network, space-based network controller, and satellite router, including b business access, air interface business resource request, core network business request, and data transmission sub-processes.

When an idle terminal detects that there is traffic data to be sent, it first initiates and completes the network business access process to the access gateway, and then triggers the core network-side business request process. The access gateway performs protocol conversion mapping and completes the tunnel resource application on the core network side. The terminal encapsulates the business data with labels, which are mapped by the access gateway to QoS flows and sent to the core network user plane after landing at the ground station. The activity diagram model can run and verify the correctness of the interaction process details (shown in Fig. 6).

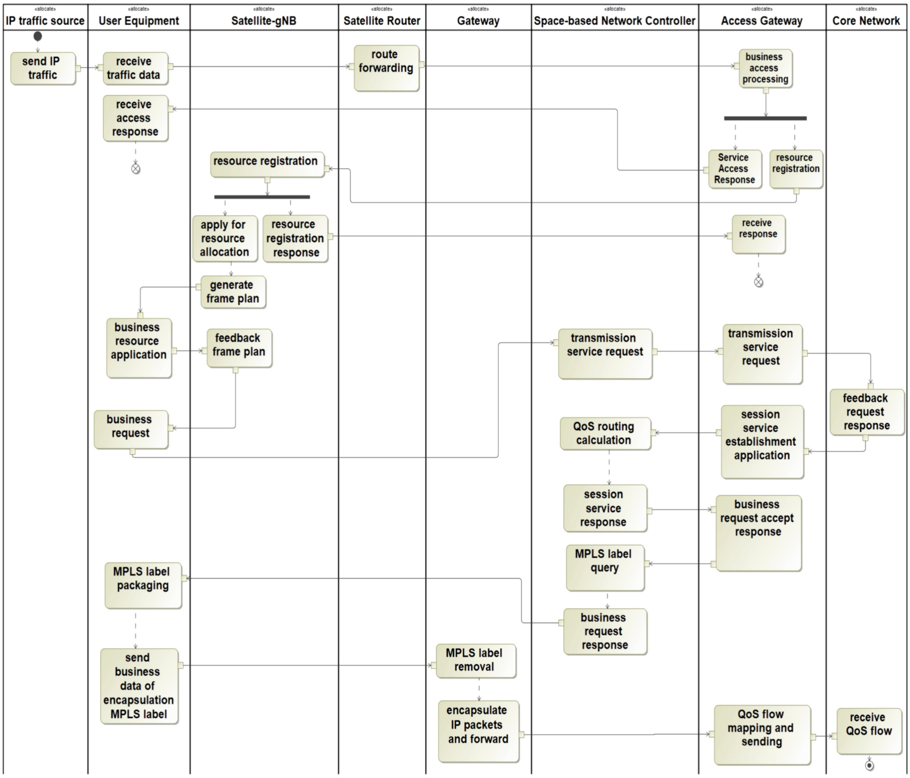

Fig. 6. Activity diagram of equipment to ground network communication process

4.3 Satellite Communication Payload Logical Architecture Modeling and State Machine Analysis

Taking the core software in satellite communication payloads as an example, we construct the logical architecture of software module interaction using an Internal Block Diagram (IBD) (shown in Fig. 7) and state machine description. The software blocks include the satellite mission computing block, payload management block, satellite routing block, user link signal processing block, user link protocol stack block, and feed link signal processing block.

The payload management software completes the initialization and configuration of communication payload hardware and software under the control of the satellite mission computer, as well as the loading of other software modules. The satellite route completes the information exchange between payloads and the inter-satellite routing by ISL. The user link signal processing software completes the physical and link layer processing of the user link. The user link protocol stack software completes the processing of user information high-level communication protocols. The feeder link software completes the physical and link layer processing of the feed link and exchanges information with the satellite router.

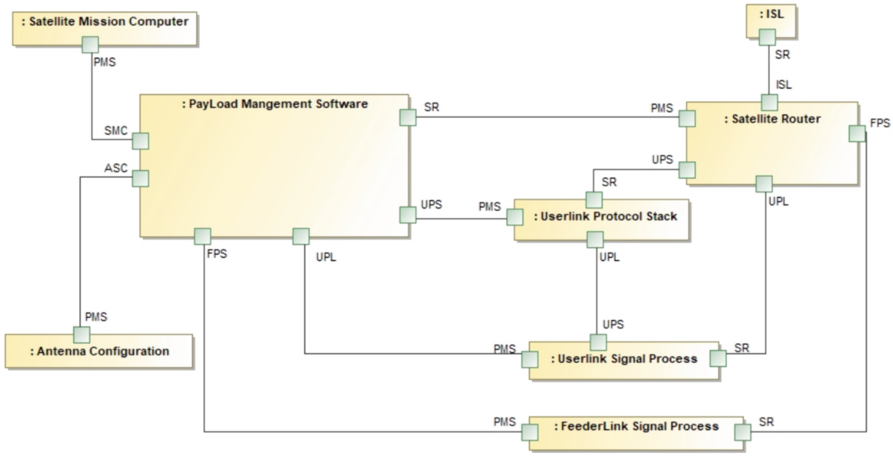

Fig. 7. LEO communication payload logic architecture

The state machine diagram of the user link protocol stack in IBD. It has three states (shown in Fig. 8) including:

The operational flow of three state machines is described as follows.

- The software loading and self-test functions are completed under the payload configuration information.
- The configuration parameters are parsed under the control of software parameter configuration information.
- The user protocol stack processing is completed, and the network layer information is sent to the internal satellite exchange routing module.

4.4 Model-Integrated Simulation Analysis

The previous description is based on SysML to conduct requirements analysis, behavioral design, and architectural design for the LEO satellite communication system. The approach is integrating behavioral diagrams and parameter diagrams in MagicDraw with domain simulation software such as Matlab, and STK to establish joint simulation. Taking Doppler simulation as an example, a simulation diagram for Doppler in the user link is provided, using MagicDraw joint Matlab (shown in Fig. 9).

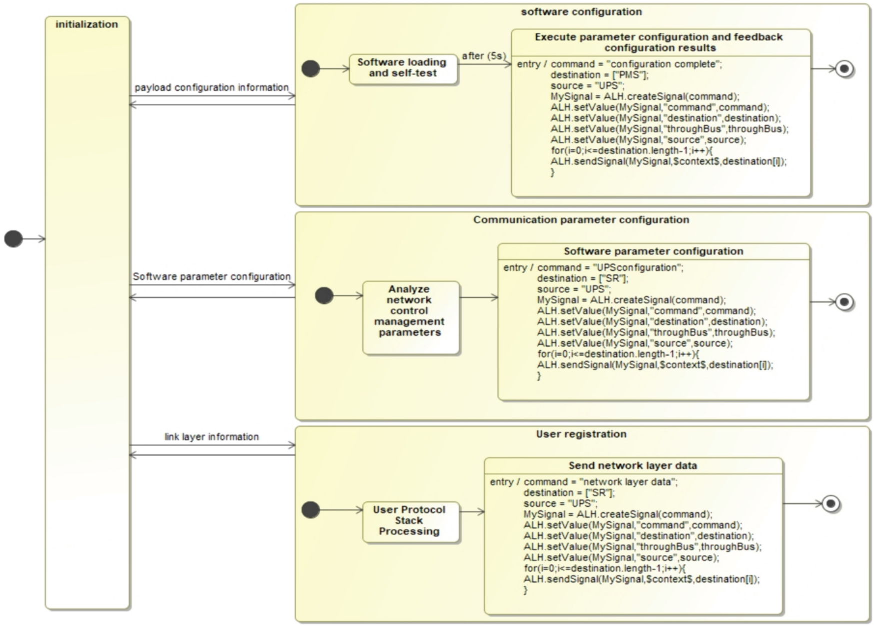

Fig. 8. Userlink protocol stack state machine

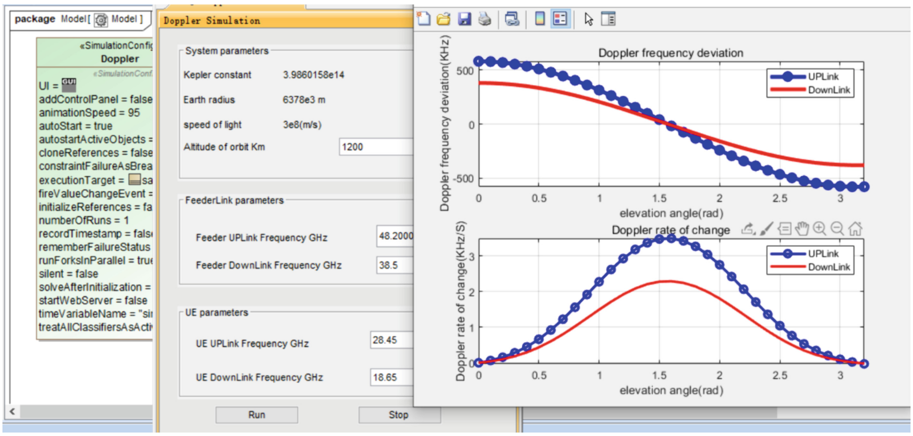

Fig. 9. Parameter model diagram and Matlab doppler joint simulation

5 Conclusion

In this paper, using the SysML language of MBSE, the requirements of the access network, transport network, and core network in the LEO satellite communication system were taken as the main thread, and the design methods such as requirements decomposition, system architecture, key activities, and logical architecture were analyzed from different perspectives. Compared with traditional document-based design methods, SysML for system design can better understand the interactions between subsystems, greatly improving design efficiency and achieving model-based maintenance, and reuse capabilities throughout the lifecycle.

The next step is refining the satellite payload model, communication process model, and key indicator tracing modeling work. In addition, through the toolchain, the integration of SysML diagrams with domain simulation software such as Matlab, STK, is achieved to seamlessly connect architecture simulation with domain simulation. This will enable interactive modeling between the activity model, parameter model, and simulation model under mission-driven, realizing full-process simulation.

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